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THE INFLUENCE OF MASS AND ENVIRONMENT ON THE EVOLUTION OF EARLY-TYPE GALAXIES

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ABSTRACT

We report on a uniform comparative analysis of the fundamental parameters of early–type galaxies at $z\sim1$ down to a well defined magnitude limit ($M_B \leq -20.0$ in the field and $M_B \leq -20.5$ in the clusters). The changes in the $\mathcal{M}/L_B$ ratio from $z\sim1$ to today are larger for lower mass galaxies in all environments, and are similar in the field and in the clusters for galaxies with the same mass. By deriving ages from the $\mathcal{M}/L_B$ ratio, we estimate the formation redshift for early-type galaxies as a function of galaxy mass and environment. We find that the age of early-type galaxies increases with galaxy mass (downsizing) in all environments, and that cluster galaxies appear to have the same age within 5% as field galaxies at any given galaxy mass. The first result confirms similar ones obtained by other means, while the second one is controversial. The most recent incarnation of the hierarchical models of galaxy formation and evolution is capable of explaining the first result, but predicts that cluster galaxies should be older than field galaxies. We also find a total lack of massive early–type galaxies ($\mathcal{M} > 3\times10^{11}\mathcal{M}_\odot$) with a formation redshift smaller than 2, which cannot be due to selection effects.

Subject headings: cosmology: observations — galaxies: elliptical and lenticular, cD — galaxies: evolution — galaxies: formation — galaxies: high redshift

1. INTRODUCTION

Early–type galaxies (ETG) contain most of the visible mass in the Universe (Renzini 2006) and are thought to reside in the highest density peaks of the underlying dark matter distribution. Therefore, understanding their evolution is crucial for understanding the evolution of galaxies and structures in general. In the 3-dimensional space of their main parameters (the effective radius R_e, the central velocity dispersion σ, and the average surface luminosity within R_e, $\langle I\rangle_e = L/2\pi R_e^2$), ETG concentrate on a plane thus called the Fundamental Plane (FP, Djorgowski & Davis 1987; Dressler et al. 1987). This implies that, besides being in virial equilibrium, ETG show a striking regularity in their structures and stellar populations (e.g., Renzini & Ciotti 1993), which allows, at least at a first order, to use their main observables for deriving the galaxy mass and $\mathcal{M}/L$ ratio. For instance, assuming $R^{1/4}$ homology, the mass is given by (Michard 1980; see also Cappellari et al. 2005):

$$\mathcal{M} = 5R_e\sigma^2/G. \quad (1)$$

Moreover, the slope of the FP can be interpreted as a systematic variation of the $\mathcal{M}/L$ ratio along the plane by a factor of ~ 3 (e.g., Ciotti, Lanzoni & Renzini 1996). At high redshift the FP is known to stay thin, and its intercept shows an offset with respect to the local one that corresponds to a change in $\mathcal{M}/L$ consistent with passive luminosity evolution (see Renzini 2006 and references therein). If ascribed to differences in the stellar populations, the observed changes in the $\mathcal{M}/L$ ratio can be used to infer the ages of ETG. We report on a comparative analysis of the best data on the fundamental parameters of ETG at $z\sim1$, the highest redshift for which these data are currently available, obtained from recent spectroscopic observations with 8-10m class telescopes, complemented with deep imaging with the Hubble Space Telescope. Using the Universe as a time machine and profiting from the large leverage provided by the redshift, we infer ages for ETG and analyse them as a function of galaxy mass and environment. We assume a flat Universe with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70$ km s^{-1}Mpc^{-1}, and we use magnitudes based on the Vega system.

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2. BACKGROUND

Recent studies (di Serego Alighieri et al. 2005; Treu et al. 2005; van der Wel et al. 2005) of the FP of ETG in the field at $z\sim1$, in the rest-frame B-band, down to relatively faint luminosities ($M_B \leq -20.0$), and hence small masses, demonstrate that, in addition to the offset, the FP at $z\sim1$ also shows a different slope. This implies that the galaxy $\mathcal{M}/L_B$ ratio evolves with redshift in a way that depends on the galaxy mass. By comparing the $\mathcal{M}/L_B$ ratio of field ETG to that of massive ($\mathcal{M} > 10^{11}\mathcal{M}_\odot$) ETG in clusters, a faster evolution of $\mathcal{M}/L_B$ for the less massive galaxies has been derived, and it is interpreted as a manifestation of downsizing, i.e. the tendency of smaller galaxies to have later or more prolonged star formation histories than the massive ones (Cowie et al. 1996).

Very recently the high-z FP of the ETG has been studied in two clusters (RX J0152.7−1357 at z=0.835 and RX J1226.9−3332 at z=0.892), reaching a similarly faint limiting absolute magnitude ($M_B \leq -20.5$), also in the rest-frame B-band (Jørgensen et al. 2006). This has pointed out that, also in the clusters, the slope of the FP changes with redshift, a manifestation of downsizing even in high density environments.

Unfortunately, because of an error in the calibration of the galaxy luminosities used by Jørgensen et al. (2006), the photometry for the two clusters should be offset to brighter luminosities with a factor $(1+z)$. Correcting for this error corresponds to an offset in $logL$ to brighter luminosities with $log(1+z)$, which is 0.26 and 0.28 for RX J0152.7–1357 ($z = 0.835$) and RX J1226.9+3332 ($z = 0.892$) respectively. Therefore the cluster data, which we have used in the published version of this letter (ApJ 647, L99), should be changed and we present here a corrected version of our original letter (see also the Erratum to ApJ 647, L99).

3. THE FORMATION EPOCH OF CLUSTER AND FIELD EARLY–TYPE GALAXIES

We make a uniform comparison of these results on the high redshift FP (Fig. 1) and on the consequent variations of the $\mathcal{M}/L_B$ ratio (Fig. 2), both in the field, by using the samples of di Serego Alighieri et al. (2005) and of Treu et al. (2005), and in the clusters, by using the sample of Jørgensen et al. (2006). As a reference in the local Universe, we use new data for the Coma cluster (Jørgensen 1999; Jørgensen et al. 2006). The figures show that the change in $\mathcal{M}/L_B$ between ETG at high redshift and the local ones decreases with the galaxy mass and is very similar in the clusters and in the field. However, since the clusters are at a slightly lower redshift, a deeper analysis is necessary to show this more clearly. The usual way to achieve this purpose is to compare the $\mathcal{M}/L_B$ ratio of the high redshift ETG with the corresponding ratio obtained for massive ($\mathcal{M} \geq 10^{11}\mathcal{M}_\odot$) cluster ETG at the same redshift, as compiled and parameterized by van Dokkum & Stanford (2003). However this analysis is unsatisfactory, since the massive cluster ETG are not necessarily a uniform class, and, by construction, such a procedure prevents one from studying the lower mass cluster galaxies. What is of interest is how the star formation history of ETG, or at least their average stellar age, depends on both galaxy mass and environment. We analyse this by interpreting the changes in $\mathcal{M}/L_B$ as differences in the ages of the stellar populations[1]. While the star formation histories of some ETG could have had multiple episodes of star formation (Treu et al. 2005), we can only estimate luminosity weighted average stellar ages, by using single stellar population models. We therefore infer galaxy ages using the relation between $\mathcal{M}/L_B$ and age obtained by evolutionary population synthesis models (Maraston 2005, see also http://www-astro.physics.ox.ac.uk/∼maraston/SSPn/ml/), and assuming that the model stellar mass is proportional to the dynamical mass obtained from equation (1). Since the $\mathcal{M}/L$–age relation depends both on the stellar initial mass function (IMF) and on the metallicity, we adopt a Kroupa (2001) IMF, which is known to better reproduce the characteristics of low and high redshift galaxies. Moreover we estimate the galaxy metallicity from the observed velocity dispersion following Thomas et al. (2005; see also Annibali et al. 2006), and we assume that this relationship does do not evolve with redshift, as in the case of passive evolution. Given the values of $\mathcal{M}/L_B$ and metallicity for every galaxy in our sample, ages have been inferred by means of a spline interpolation of the population synthesis model results. Then, the lookback time to formation has been derived by using the Universe as a time machine and exploiting the large leverage provided by the considerable distance of the observed ETG. The uncertainties on the age estimates have been computed taking into account the known errors in $\mathcal{M}/L_B$, as well as the uncertainties on the estimated metallicities, due to the known errors in the velocity dispersion measurements and to the observed scatter in the metallicity vs. velocity dispersion relation (Thomas et al. 2005).

The resulting formation epochs of ETG are shown in Figure 3 as a function of galaxy mass, both for the cluster and for the field environment. The estimated ages for the two brightest cluster galaxies (#1567 in RXJ0152.7-1357, and #563 in RXJ1226.9+3332 Jørgensen et al. (2006)), are 23.4 ± 2.6 and 16.4 ± 0.9 Gyr, respectively, and are not included in Fig. 3 (see below for a discussion about these large ages). A clear and important result is the lack of young massive ETG. In particular all ETG with $\mathcal{M} > 3 \times 10^{11}\mathcal{M}_\odot$ have a lookback time to formation larger than 10 Gyr and have a formation redshift larger than 2. Clearly this cannot be the result of a selection effect, since relatively young massive ETG could not escape from the available surveys.

Confirming the analysis of the evolution of $\mathcal{M}/L_B$ given at the beginning of this section, we find that more massive galaxies are older than lower mass ones in all environments, and that cluster galaxies have the same age within 5% as field galaxies with the same mass, in the whole mass range (see Fig. 4). A similar dependence of the age on the mass has already been obtained by an analysis of the absorption line indices of a sample of local ETG (Thomas et al. 2005). However Thomas et al. (2005) find that ETG in clusters are older than those in the field by about 2 Gyr. Given the number of objects in the samples that we have examined and the errors in the estimate of their age, we should have seen such a systematic age difference, if it were present in the data that we have used. We argue that using the Universe as a time machine should be more powerful than "archaeology" on local galaxies, since galaxies are caught closer to the action. Interestingly, also the Coma ETG show the downsizing effect, and their formation redshifts are very consistent with those of $z{\sim}1$ ETG (Jørgensen 1999). This suggests that the $z{\sim}1$ samples examined here are not much affected by the progenitor bias (van Dokkum & Franx 2001; di Serego Alighieri et al. 2005). Thus, our results suggest that the first ETG to form are the most massive

[1] It has been shown that other possible interpretations, i.e. systematic structural changes and partial support by rotation, can only explain a small fraction of the observed differential evolution of $\mathcal{M}/L_B$, and that this evolution correlates with the rest-frame $U-B$ colour, thereby providing independent evidence for changes in the stellar populations (di Serego Alighieri et al. 2005).

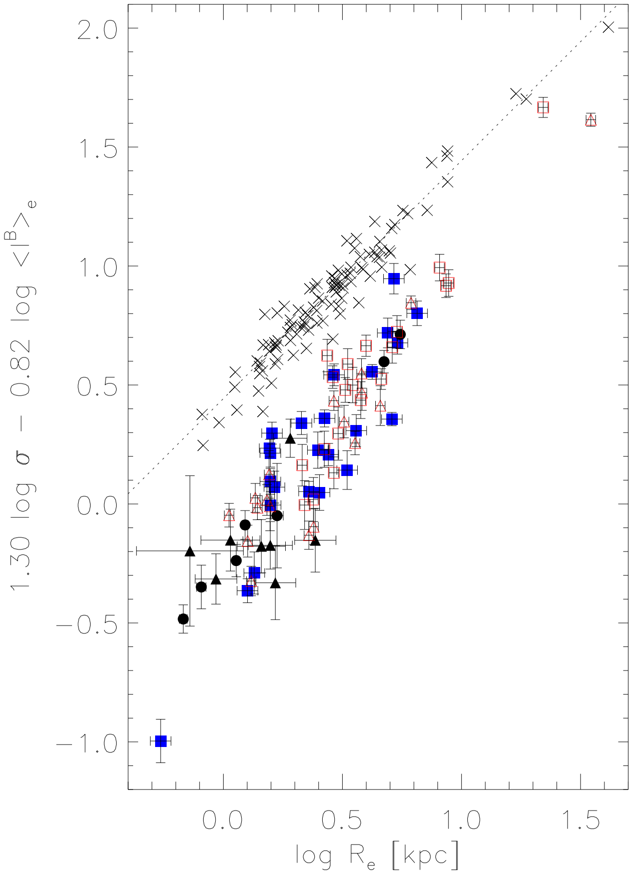

Fig. 1.— The Fundamental Plane seen edge–on for local ETG in the Coma Cluster (Jørgensen et al. 2006) (black crosses), for field ETG at $z{\sim}1$ from the K20 survey (di Serego Alighieri et al. 2005) both in the CDFS field (filled black circles) and in the Q0055 field (filled black triangles), for field ETG at $z{\sim}1$ in the GOODS area (Treu et al. 2005) (filled blue squares), and for the ETG in two clusters (Jørgensen et al. 2006) at z=0.835 (open red squares) and at z=0.892 (open red triangles). The dashed line is the best fit plane to the Coma cluster galaxies. Compared to the local one, the FP at high redshift is offset and rotated in all environments.

ones independently of the environment.

Although the absolute ages that we derive are somewhat model dependent, are affected by an approximate metallicity estimate, and obviously depend also on the adopted cosmological parameters, we stress that the *trends of age differences* between high redshift and local ETG, and between galaxies with different masses and in different environments are much more robust.

One of the uncertainties affecting the age estimates derives from the assumption of structural homology when computing masses through equation (1). It is well known that ETG show a systematic departure from homology, both locally (Caon, Capaccioli & D'Onofrio 1993; Gutièrrez et al. 2004; Gavazzi et al. 2005) and at $z{\sim}1$ (di Serego Alighieri et al. 2005) and that more precise dynamical masses can be obtained taking these deviations into account, using the Sérsic (1968) profile, to describe the observed surface brightness distribution, instead of the $R^{1/4}$ law (Bertin, Ciotti & Del Principe 2002). These mass estimates can be up to $\sim 50\%$ higher

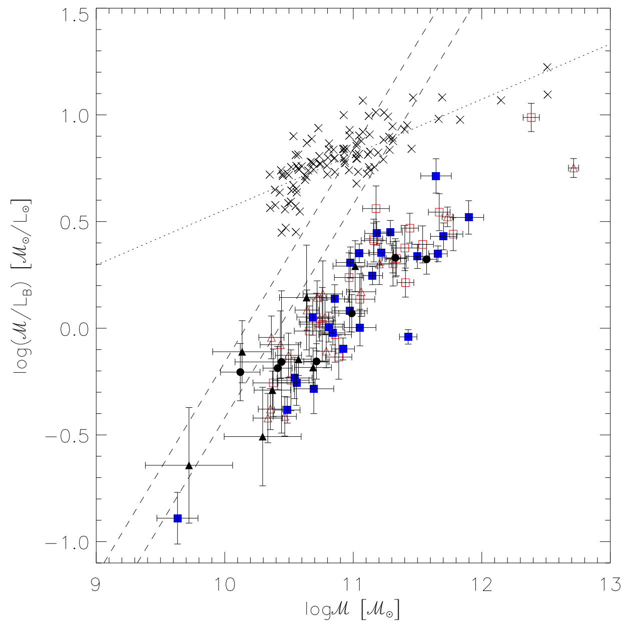

Fig. 2.— The $\mathcal{M}/L$ ratio in the B-band as a function of galaxy mass for the ETG samples shown in figure 1 (same symbols). The dotted line is a fit to the Coma ETG, while the upper and lower dashed lines represent the $M_B = -20.0$ and $M_B = -20.5$ magnitude limits of di Serego Alighieri et al. (2005) and of Jørgensen et al. (2006) respectively. The changes in $\mathcal{M}/L_B$ from high redshift to $z = 0$ decrease with galaxy mass in all environments and are similar in the field and in the clusters.

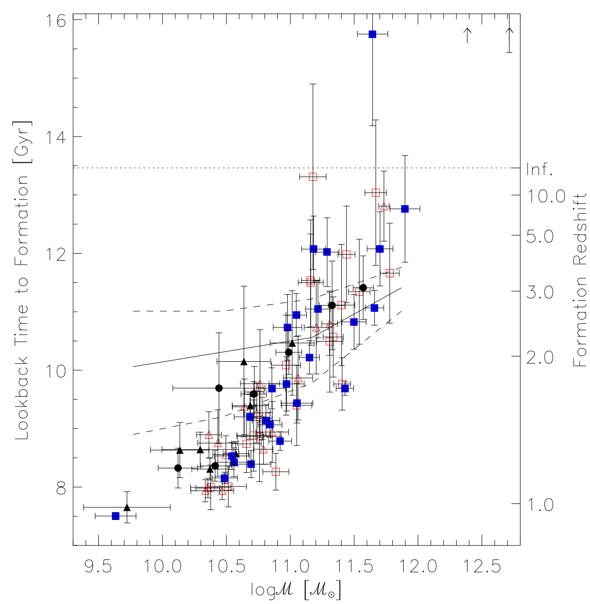

Fig. 3.— The formation epoch for the ETG shown in figure 1 (same symbols), evaluated as explained in di Serego Alighieri et al. (2006). The two upward pointing arrows indicate that the two most massive cluster ETG are out of the figure (their ages amount to 16.4 and 23.4 Gyr). The continuous line shows the median model ages obtained by De Lucia et al. (2006) from a semianalytic model of hierarchical galaxy evolution, while the dashed lines are their upper and lower quartiles. More massive ETG form earlier in all environments, and the ages are not influenced by the environment.

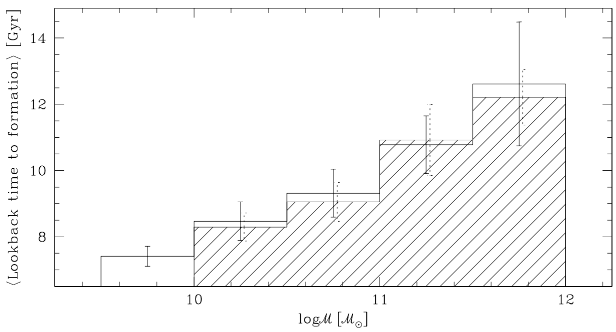

FIG. 4.— Histogram of the average lookback time to formation per mass bin for the high redshift ETG in the field and in the clusters (hatched). The error bars (dotted for the clusters) show the standard deviation due to the galaxy–to–galaxy variations in each mass bin.

than those obtained assuming homology for the low mass galaxies, but can also be lower by up to 20% for the high mass galaxies (di Serego Alighieri et al. 2005). Unfortunately we do not have Sérsic indices for all the ETG examined here, but we have checked on the K20 field samples of di Serego Alighieri et al. (2005) that the ages estimated by taking non homology into account do not vary substantially from those given in Fig. 3 and 4, computed using eq. (1). Since the brightest cluster galaxies are known to deviate from the $R^{1/4}$ profile, and if the influence of dark matter increases in high mass galaxies, these factors could lead to an overestimate of the the ages of the most massive ETG in the cluster sample.

The influence of selection effects is shown by the dashed lines in Fig. 2, which represent the magnitude limit of the K20 field samples of di Serego Alighieri et al. (2005) and of the two high redshift clusters of Jørgensen et al. (2006). These samples are affected by selection only for $\mathcal{M} < 4 \times 10^{10}\mathcal{M}_\odot$, while the different slope in the high redshift samples compared to the local one is clearly visible also for larger masses, thus cannot be totally due to selection effects (see also van der Wel et al. (2005)).

Very recently the largest high resolution simulation of the growth of cosmic structure in the hierarchical formation scenario (the Millennium Run, Springel et al. 2005) has been used to study how the ages of ETG depend on environment and on galaxy mass (De Lucia et al. 2006). In this model, since merging of smaller galaxies is an important ingredient for the formation of ETG, the galaxy formation time, which is when most of its stars formed, and the galaxy assembly time, which is when stars assembled in the single galaxy that we observe, are considered separately (De Lucia et al. 2006). Our dating based on changes in the $\mathcal{M}/L_B$ ratio relates to when the stars formed, rather than to when they assembled. The semi-analytic hierarchical model of De Lucia et al. (2006) is able to reproduce the already known result, i.e. that the formation times are earlier for more massive ETG, although the downsizing effect is considerably steeper in the model than in the data (see Fig. 3), but clearly predicts that cluster galaxies should be older than field galaxies, which is not what we observe.

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